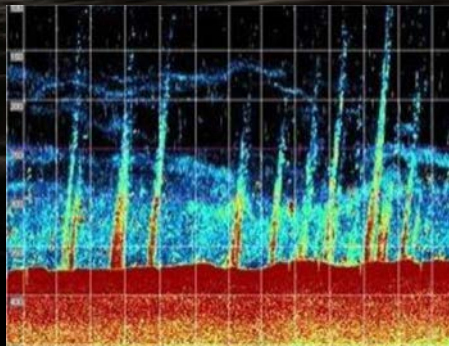# METHANE HYDRATE

SCIENCE AND TECHNOLOGY: A 2017 UPDATE

Evaluating the resource potential of methane hydrate and understanding its role in global climate change

INTRODUCTION

Methane hydrate represents a potentially vast methane resource for the United States and the world. Once thought to be rare in nature, gas hydrates are now known to occur in great abundance in association with arctic permafrost and in the shallow sediments of the deep-water continental shelves. The most recent estimates of gas hydrate abundance suggest that they contain more organic carbon than all the world's oil, gas, and coal combined.

The mission of the U.S. Department of Energy's Methane Hydrates R&D Program, managed by the National Energy Technology Laboratory is to collaborate nationally and internationally to advance the scientific understanding of naturally occurring gas hydrates. Specific goals are to develop a more complete understanding of the resource potential of methane hydrate and its role in climate change. In pursuit of this mission, the program is proceeding along three parallel paths. The first path is to confirm the scale and nature of the potentially recoverable resource through drilling and coring programs. The second is to develop the technologies to safely and efficiently find, characterize, and recover methane from hydrates through a combination of field testing, numerical simulation, and controlled laboratory experimentation. The third is to develop a more thorough understanding of gas hydrate's role in the natural environment, including its linkages to global climate change.

Going forward, the Methane Hydrate R&D Program is being designed to fill in the gaps in knowledge along the three paths described above. The first path—confirming the scale and nature of the potentially recoverable resource—will be achieved through pressure core sampling and high-resolution seismic imaging in the Gulf of Mexico, U.S. Atlantic margin, and the rest of the nation. The second path—developing technologies to safely and efficiently find, characterize, and recover methane from hydrates—will be pursued by optimizing approaches to site review and project logistics, developing new Alaska science wells for testing depressurization; and optimizing arctic and deepwater production systems. The third path—understanding the role of gas hydrates in the environment and its linkages to climate change—will be realized through arctic and Atlantic margin field work and developing and refining predictive climate models.

This document is intended to provide a background on what is known about methane hydrate (Chapter 1); a status update on current Methane Hydrate R&D Program activities (Chapter 2); and a description of R&D goals as projected into the near-future (Chapter 3). The U.S. Methane Hydrates R&D Program has made significant advances over the past 15 years, and a number of projects are currently underway that will advance our understanding of this fascinating resource even more. Additional R&D will be tailored to address critical remaining questions and challenges.

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ICE THAT BURNS

Pressure, temperature, and availability of sufficient quantities of water and methane are the primary factors controlling methane hydrate formation and stability.

What is Methane Hydrate?

Methane hydrate is a naturally-occurring clathrate in which a host lattice of water-ice encloses guest molecules of methane. The gas molecules are not chemically bound to the water molecules but instead are trapped within their crystalline lattice. The resulting substance looks remarkably like white ice, but it does not behave like ice. When methane hydrate is "melted," or exposed to pressure and temperature conditions outside those where it is stable, the solid crystalline lattice turns to liquid water, and the enclosed methane molecules are released as gas. This process, called dissociation, can be demonstrated by lighting a match next to a piece of methane hydrate; the heat from the match will cause the hydrate to dissociate, and the methane molecules will be ignited as they are released. This results in the curious spectacle of what appears to be burning ice.

Methane hydrate is a material that only occurs in particular environments, because it requires very specific physical conditions to form and remain solid. Pressure, temperature, and availability of sufficient quantities of water and methane are the primary factors controlling methane hydrate formation and stability.

Model of a methane molecule enclosed in water-molecule "cage."

Methane hydrate dissociating with the methane ignited – "burning ice."

The graphs below are phase diagrams, showing the pressure and temperature ranges where methane hydrate is able to form. The horizontal axis shows temperature, increasing from left to right, and the vertical axis shows depth of burial, increasing from top to bottom. Because fluid pressure increases with depth below the surface of the earth or the ocean, depth serves as a proxy for fluid pressure in hydrate phase diagrams.

The curved red line is the methane hydrate phase boundary. Above and to the right of this boundary, temperatures are too warm, and pressures are too low for methane hydrate to form, so methane can only be present as a gas. Below and to the left of this boundary, solid methane hydrate is able to form and remain stable, because temperatures are sufficiently low, and fluid pressures are sufficiently high to sustain the solid phase.

Other factors can affect the stability of methane hydrate. For example, higher salt content in pore water within sediments can restrict hydrate formation, just like road salt keeps ice from forming on highways. Elevated salinity has the effect of shifting the hydrate phase boundary to the left—essentially requiring colder temperatures to form hydrate. Similarly, the presence of small amounts of gases other than methane, such as carbon dioxide (CO_2), hydrogen sulfide (H_2S), or heavier hydrocarbons such as ethane (C_2H_6) can act to shift the phase boundary to the right, so that hydrate can form at higher temperatures.

The depth zone where temperatures are in the range to sustain solid hydrate is called the gas hydrate stability zone and is indicated by vertical arrows on the phase diagrams shown below.
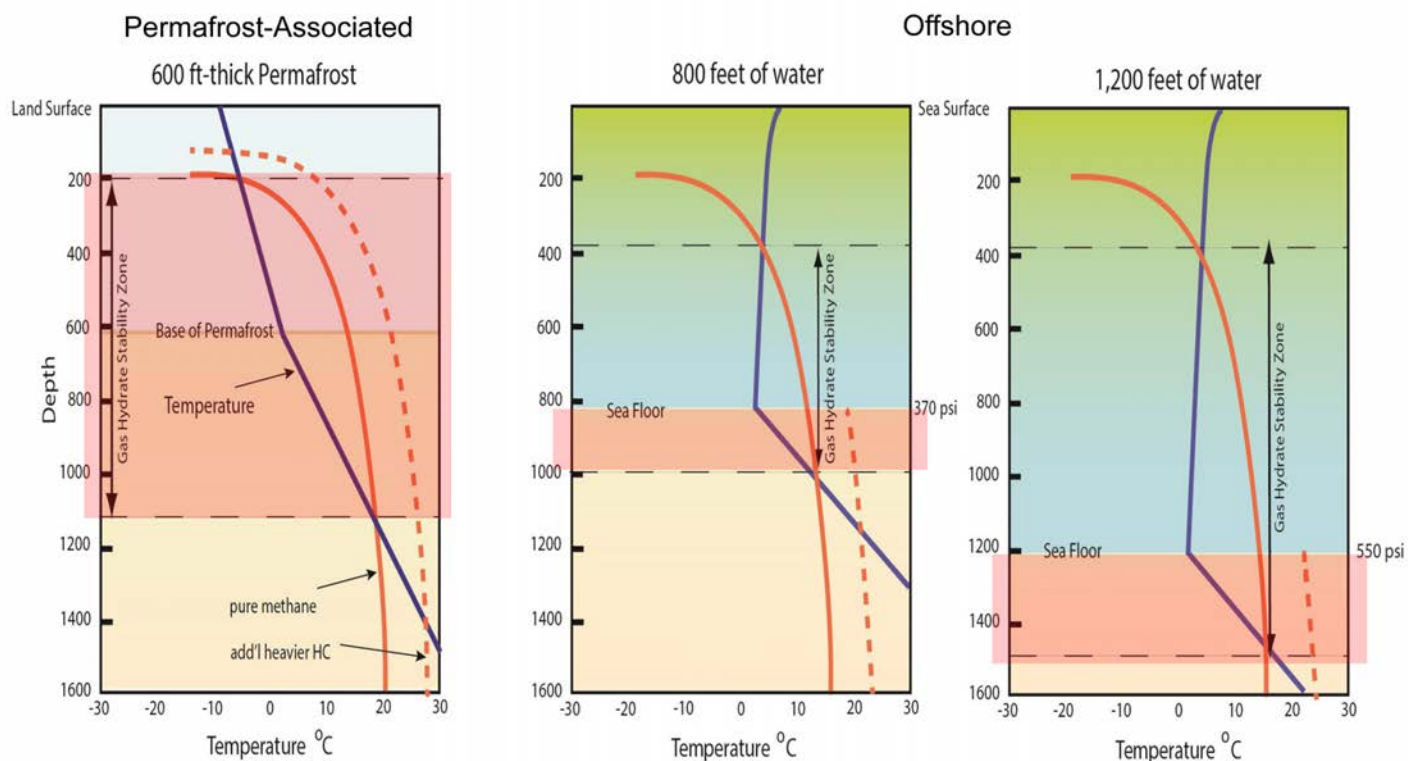
Phase diagrams showing depth and temperature ranges, in pink, where hydrate may form and remain stable.

Because methane hydrate can only remain solid at low temperatures and high pressures, it is difficult to recover methane hydrate samples intact, whether the samples are collected from the seafloor or from deeply buried sediments. As soon as a sample is brought to the Earth's surface, it will follow a pressure-temperature path that is upwards and towards the right across the phase boundary. Dissociation of hydrate into water and methane will occur, unless the sample is maintained during retrieval, or quickly pressurized or refrigerated after retrieval to keep it within the hydrate stability envelope.

Methane hydrate is a fairly concentrated form of natural gas. When dissociated at normal surface temperature and pressure, one cubic foot of solid methane hydrate will release about 164 cubic feet of methane gas. This is one of the reasons people are interested in methane hydrate as a potential source of methane for energy supply.
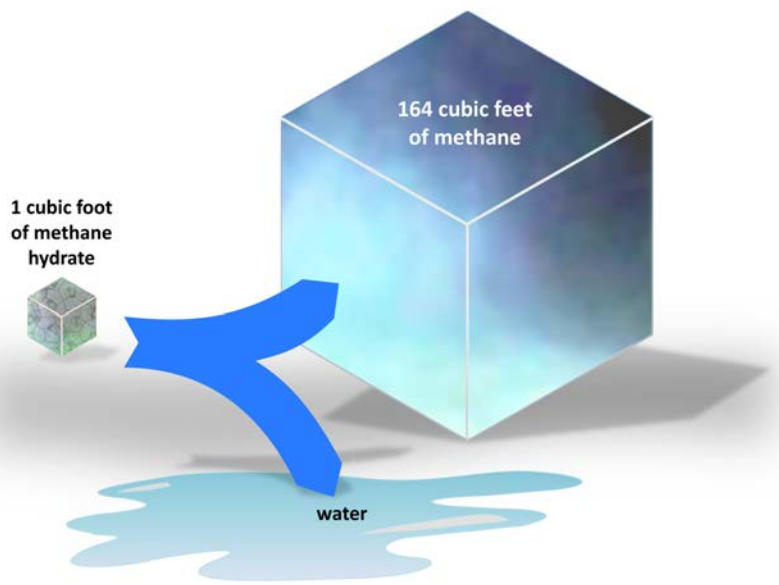
Illustration showing dissociation of hydrate into water and methane.

Where is Methane Hydrate Found?

Methane hydrate is known to occur in both terrestrial (onshore) and marine (offshore) environments throughout the world. Terrestrial deposits have been found in polar regions, hosted in sediments within and beneath permafrost. Marine occurrences have been found mainly in sediments of the Earth's outer continental margins. These are the natural settings where methane and water are present, and where pressure and temperature conditions are suitable to form and sustain hydrate.

The methane that is captured in methane hydrate may have been generated by biogenic or thermogenic processes. Biogenic methane is the common by-product of bacterial ingestion of organic matter. This is the
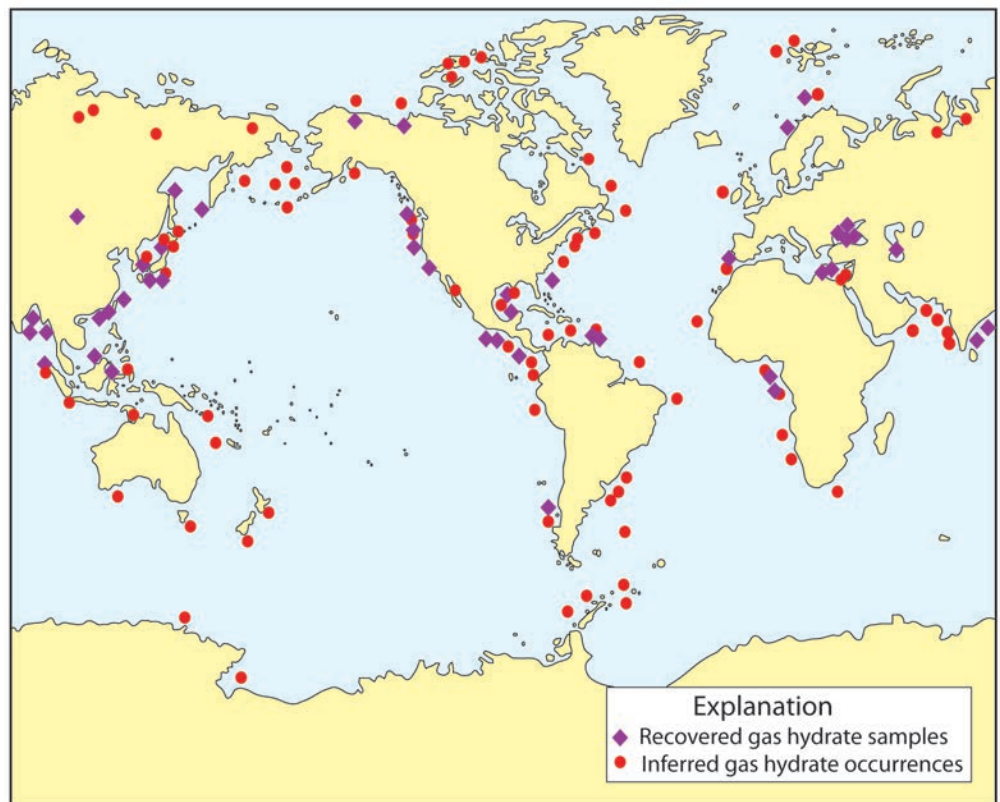
Location of sampled and inferred gas hydrate occurrences worldwide. (Map courtesy of Timothy S. Collett, USGS)

same process that produces methane in swamps, and it occurs continually within buried sediments all around the globe. Biogenic processes are capable of producing vast amounts of methane and are considered to be the dominant source of the methane trapped in hydrate accumulations in shallow seafloor sediments, as shown in the diagram below.

Thermogenic methane is produced by the combined action of heat and pressure over long periods of time in deeply buried organic material. Over time and with deep burial, organic-rich source beds are literally pressure-cooked, with the result being the production of large quantities of oil and natural gas. Along with the oil, the natural gas (largely methane, but also ethane, propane, and other gases) slowly migrates upward due to its relative buoyancy. Where sufficient quantities of gas reach the zone of hydrate stability, this gas is able to combine with water in the sediments to form methane hydrate, as shown below.

Given the pressure-temperature relationship found in deep marine environments, it might seem that hydrate could accumulate anywhere in ocean-bottom sediments where water depth exceeds about 400 meters. However, very deep sediments are generally not thought to contain large quantities of hydrate. The reason is that very deep oceans lack the high biologic productivity needed to create the organic matter that generates methane, and they lack the rapid sedimentation rates needed to deeply bury the organic matter. These conditions do exist along the continental margins—areas where the continental shelf transitions to the deep ocean. As a result, this is where large quantities of methane hydrate are thought to exist in the marine environment.
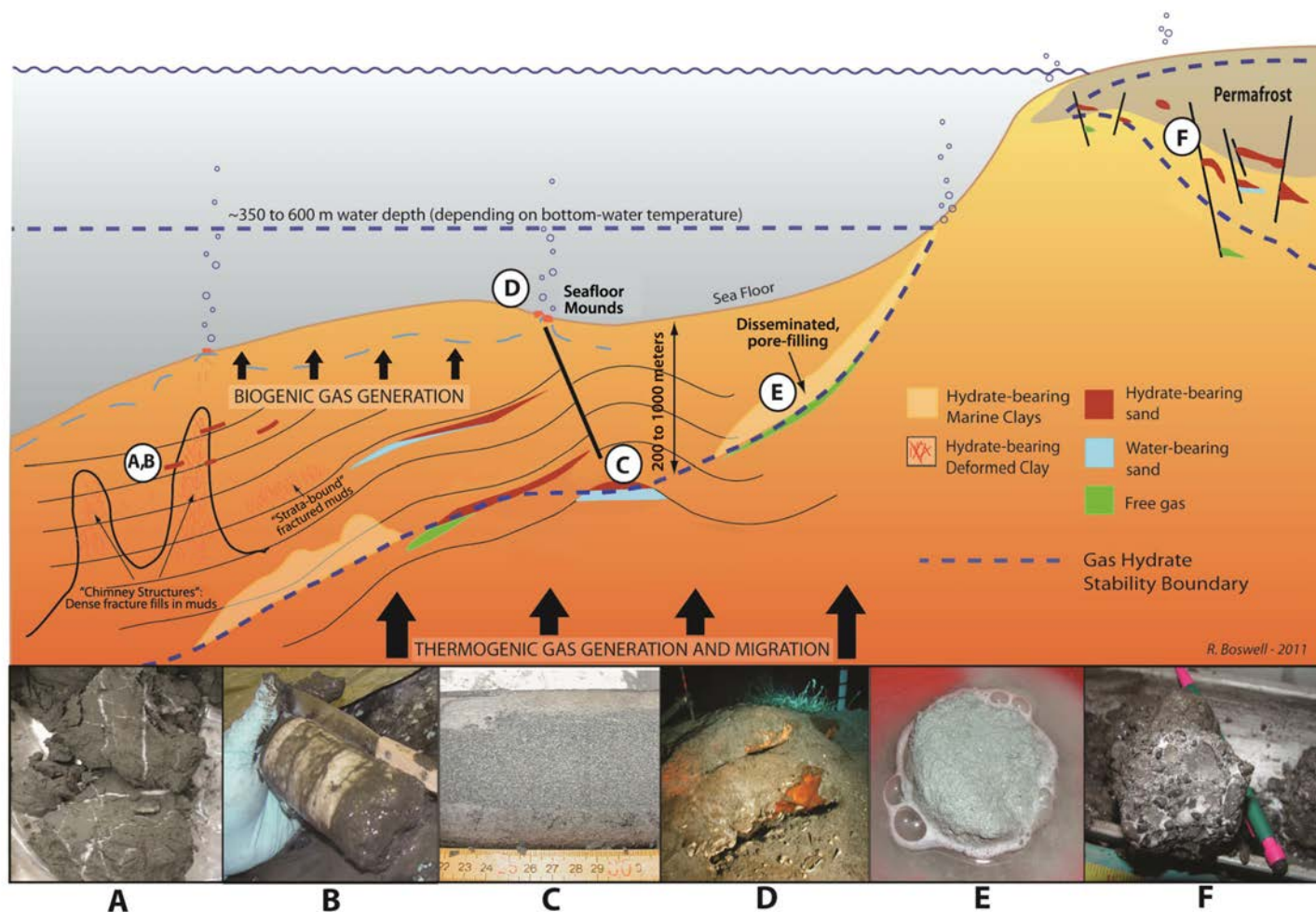
Gas Hydrate in Nature

Methane Hydrate and Global Climate

Methane hydrate deposits hold immense volumes of methane, primarily stored in sediments of the Earth's outer continental margins and polar regions. The total amount of carbon stored in these deposits amounts to many thousands of gigatons and, in fact, far exceeds the quantity of carbon that currently resides in the atmosphere. Clearly, methane hydrate has an important role in our planet's global carbon cycle, primarily as a carbon storage reservoir.

Methane is also a significant greenhouse gas, representing about 10 percent of our nation's greenhouse gas emissions in recent years. It is much less abundant and much shorter-lived in our atmosphere than carbon dioxide, but it is a potent greenhouse gas—meaning it is highly effective at trapping the sun's radiation. For all of these reasons, methane hydrate is gaining recognition as an important player in global climate processes and climate change.

Beyond these basic assertions, many questions remain. What is the best estimate for how much methane resides in methane hydrate accumulations throughout the world? A current estimate is 5,000 Gigatonnes, as illustrated below.
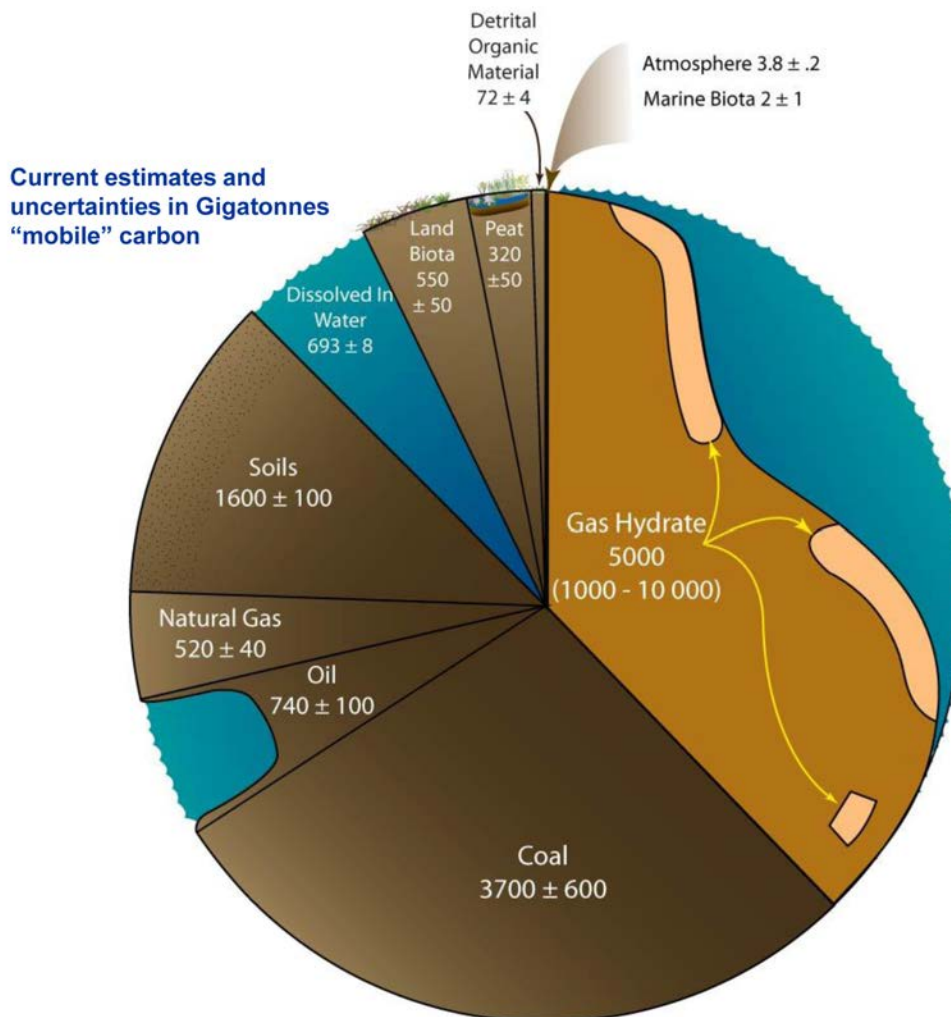
Estimates of Gigatonnes mobile carbon in gas hydrate relative to other orgainic materials and environments. (Courtesy of W. Waite, USGS).

A related question is, what is the natural methane flux from methane hydrate deposits in marine and non-marine environments? Also, what role do gas hydrates play in mediating the movement of carbon between the Earth and its atmosphere? How stable are hydrate deposits in Polar Regions, and how much do they contribute to observed methane releases? How sensitive are methane hydrate deposits to climate change in Arctic regions? How sensitive are marine hydrate deposits to warming of ocean waters? How can we most effectively minimize the risk of unintended dissociation of gas hydrates in future production scenarios?

Illuminated hydrate mound. (Photo courtesy of Scripps Institute of Oceanography).

Ice worms in methane hydrate.
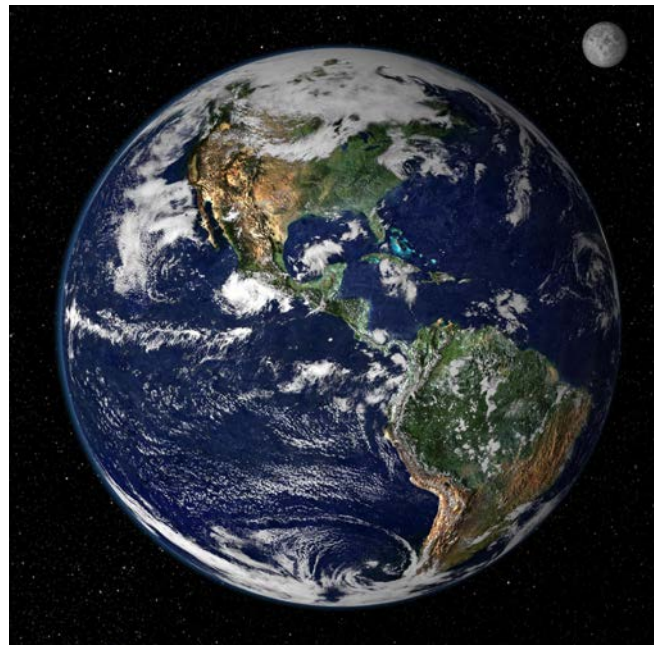
Photo credit NASA.

In recent years the U.S. Department of Energy's Office of Fossil Energy has stepped up efforts to address these and other questions. Experts from universities and national laboratories are working to quantify methane flux from hydrate in a variety of settings and to define the potential impacts of methane hydrate formation and dissociation on the global carbon cycle. Scientists are also studying natural consumption of methane by microbes in marine waters, to determine how much methane makes its way upward through the water column and to the atmosphere. Ongoing studies are also underway to improve maps of the distribution and concentration of hydrate deposits in particular geological settings. Data and results from such studies will enable methane hydrate to be more accurately incorporated into global climate models.

Fate of buried organic matter
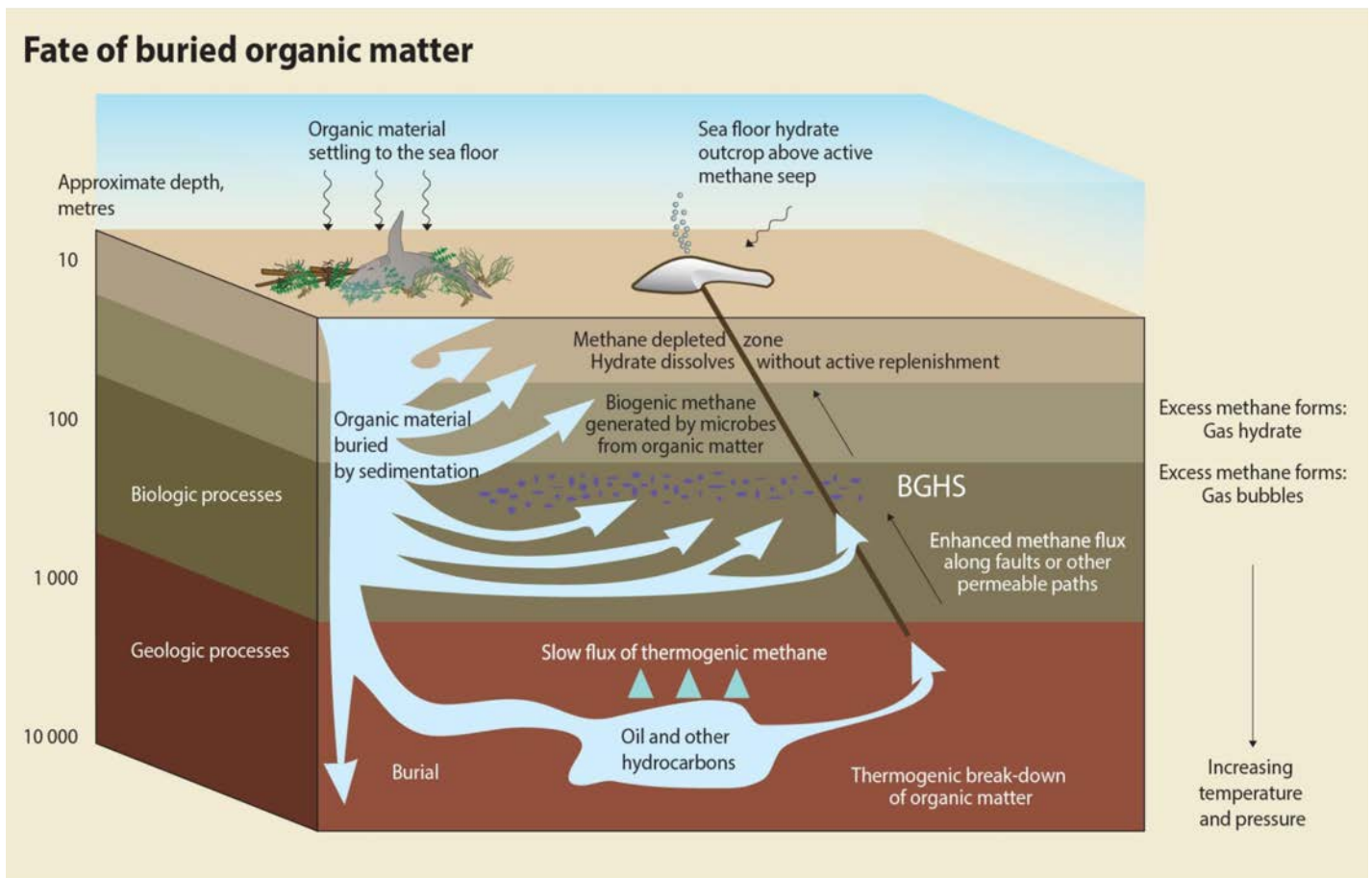
Methane creation in the environment. (Courtesy of W. Waite, USGS).
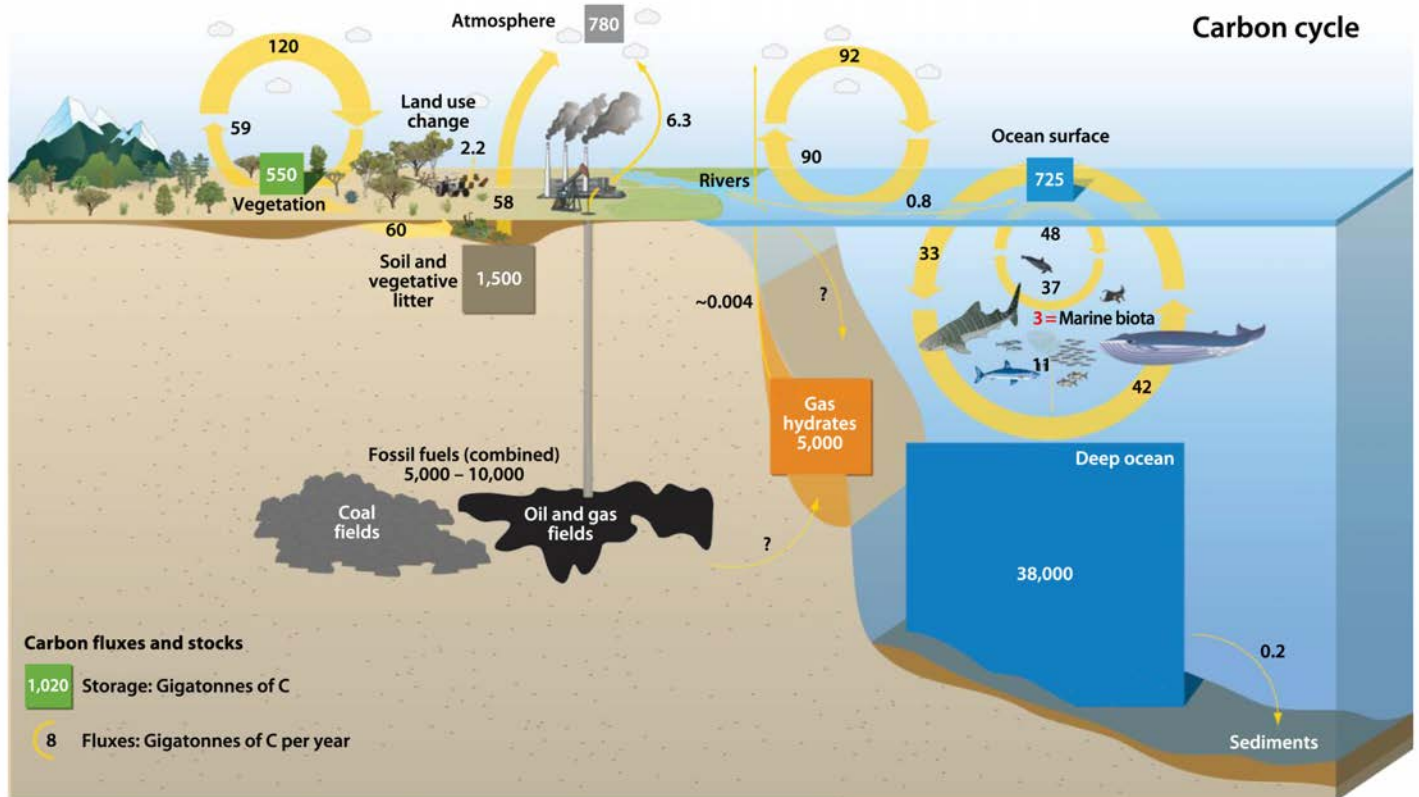
Global carbon cycle. (Courtesy of W. Waite, USGS).

On an international level, DOE program representatives have participated in recent years in an initiative launched by the United Nations Environment Program (UNEP), to develop a comprehensive review of the science and technology of gas hydrates. UNEP worked with an international steering committee and with scientists and engineers throughout the gas hydrate research community to publish Frozen Heat, A Global Outlook on Methane Gas Hydrates. This publication is organized in three volumes: Volume 1, A Review of Gas Hydrates in Nature; Volume 2, The Potential Significance of Gas Hydrates as an Energy Resource; and an Executive Summary, A 32-Page Summary of the Report. This report is intended for a global audience of policy makers, the general public, and other stakeholders. It is available online at http://www.netl. doe.gov/research/oil-and-gas/methane-hydrates.

The three-volume *Frozen Heat* publication.

Methane Hydrate as a Future Energy Resource

The worldwide volume of methane held in methane hydrate is immense. A frequently quoted estimate of the global methane hydrate resource is 20,000 trillion cubic meters, or about 700,000 Tcf. It is important to point out, however, that only a small portion of this enormous resource is likely to be harvested as an energy fuel.

Gas hydrates have the potential to provide significant supplies of clean-burning domestic natural gas to meet future energy needs. The largest domestic resources are estimated to be present in Alaska and the Gulf of Mexico. The U.S. Geological Survey (USGS) in 2008 estimated there are about 85 trillion cubic feet of undiscovered, technically recoverable gas resources in gas hydrates in northern Alaska. In the Gulf of Mexico, marine in-place gas hydrate resources in the most favorable reservoir settings have recently been assessed by the Bureau of Ocean Energy Management (BOEM) at more than 6,000 trillion cubic feet, and a 2012 report from BOEM indicated large potential resources off the U.S. Atlantic and Pacific coasts as well.

These estimates are continually refined and improved, as researchers obtain new and better information about the location and concentration of methane hydrate through direct sampling, laboratory testing, modeling, and geophysical detection.

Table 1. BOEM in-place gas hydrate resource volumes for the Atlantic, Pacific, and Gulf of Mexico Outer Continental Shelf (OCS). Units are trillion cubic feet; 1×10^{12} ft^3. Resource volumes have not been subject to geologic risk.

Region	In-Place Gas Hydrate Resources		
	Gas (TCFg)		
	95%	Mean	5%
Atlantic OCS	2,056	21,702	52,401
Pacific OCS	2,209	8,192	16,846
Gulf of Mexico OCS	11,112	21,444	34,423
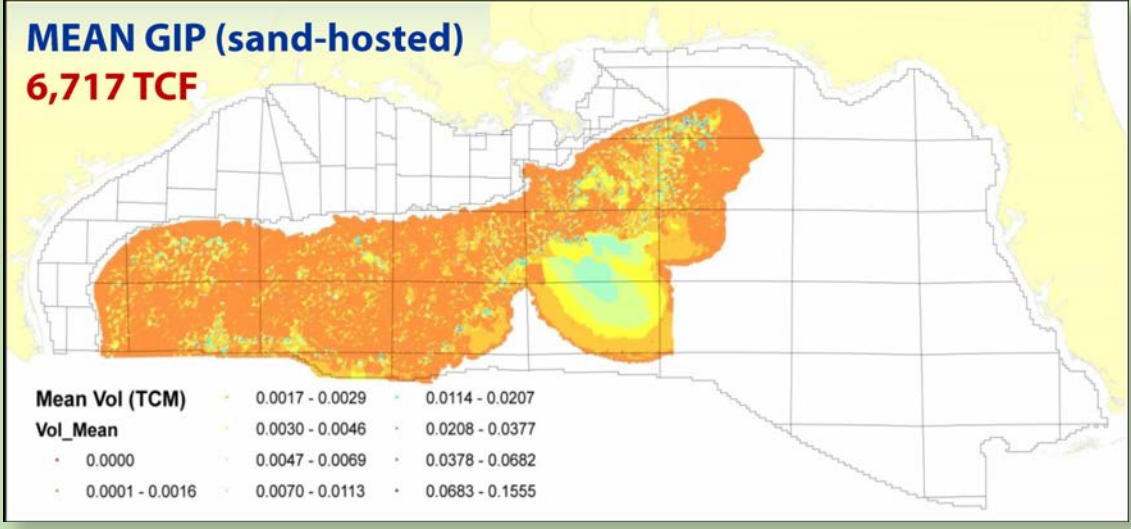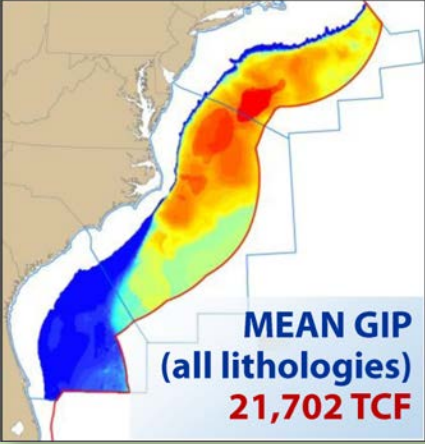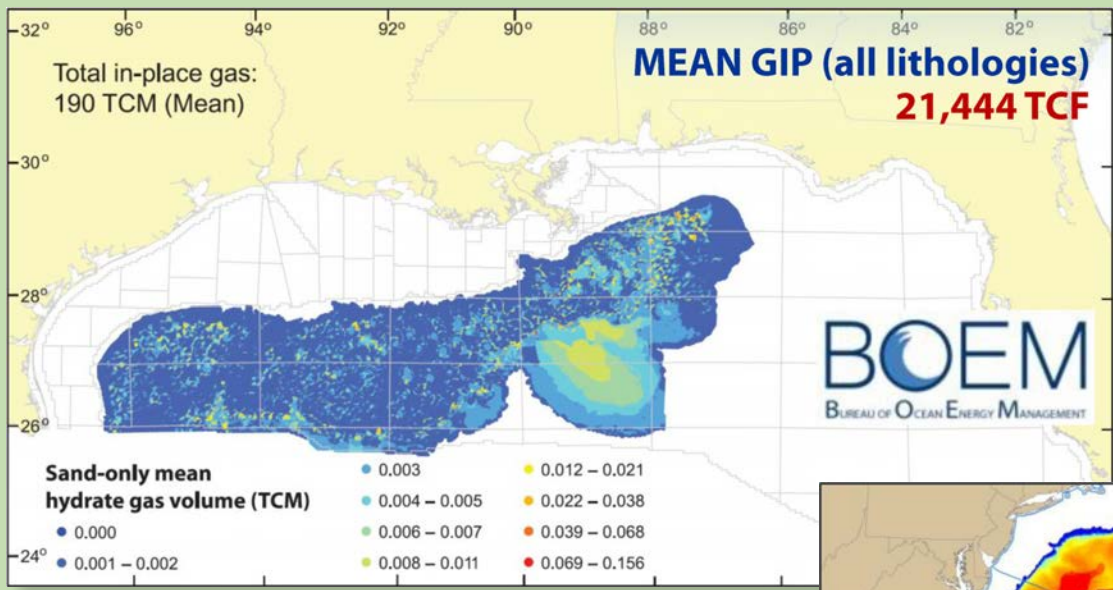
Gas hydrate in-place resource assessment by U.S. Bureau of Ocean Energy Management.

THE U.S. DEPARTMENT OF ENERGY'S METHANE HYDRATE R&D PROGRAM TODAY

The FE Hydrate Program aims to develop a comprehensive understanding of the resource potential of methane hydrates and the role that hydrates may play in climate change.

Since the passage of the Methane Hydrate Research and Development Act of 2000, the DOE has led, through its Office of Fossil Energy and the National Energy Technology Laboratory, a coordinated Methane Hydrate R&D Program in collaboration with other federal agencies, universities, industry, and international partners. The DOE program mission is to collaborate with international entities and with other U.S. government agencies to advance the scientific understanding of gas hydrates as they occur in nature. More specifically, the program aims to develop a comprehensive understanding of the resource potential of methane hydrates and the role that hydrates may play in climate change.

In keeping with this mission, the current program is structured to advance along three paths. The first path is to confirm the scale and nature of the potentially recoverable resource through drilling and coring programs. The second is to develop the technologies to safely and efficiently find, characterize, and recover methane from hydrates through a combination of field testing, numerical simulation, and controlled laboratory experimentation. The third is to better understand gas hydrate's role in the natural environment and its linkages to global climate change.

A Balanced Program

The DOE strives to manage a methane hydrate research program that is well balanced and focused on knowledge gaps in key areas including: resource characterization, production potential, and global environmental and safety impacts.

The National Research Council (NRC), in its 2010 review of the program, found that DOE's "overall management of the Program has been consistent and effective." Further, the NRC found that "the positive impact the Program is having on raising the profile of and interest in methane hydrate as a potential energy resource, and the rate at which the Program is moving toward the goal of achieving production of methane from methane hydrate accumulations are all commendable."

A 2010 review of the gas hydrate program was conducted by the National Research Council and can be found at: http://www.nap.edu/catalog/12831/realizing-the-energy-potential-of-methane-hydrate-for-the-united-states.
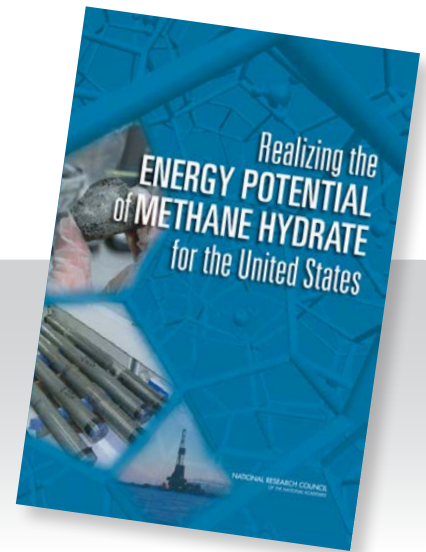
In its existing portfolio, DOE continues to focus on the objectives supported by the NRC review; "to develop a comprehensive knowledge base and suite of tools and technologies that will enable: 1) safe and economic methane production from hydrate while minimizing environmental impacts, and 2) full integration of hydrate science into our understanding of global environmental and climate processes."

International collaboration is a vital part of the program, and the DOE FE Hydrate Program is committed to working with international partners whenever feasible to achieve common goals. Such cooperation promotes open exchange of information on gas hydrate occurrences from a wide range of geologic and geographic settings. International projects also provide a framework for gaining a wide breadth of experience with field sampling and analysis tools. Recent international collaboration has been with major national R&D programs in Japan, India, and South Korea.

South Korean researchers conducting a methane hydrate science expedition.

Identifying Knowledge Gaps

Methane hydrate resource volumes, particularly marine hydrate resources that are most prospective for production, remain poorly defined. Large areas of the U.S. outer continental shelf are virtually unexplored, with only a handful of wells having been drilled for hydrate evaluation in the Gulf of Mexico and the Pacific and Atlantic seaboards.

The commercial producibility of gas hydrate reservoirs is also not well known. A limited number of production tests have been conducted to-date, with the first deepwater test occurring offshore Japan in the Spring of 2013. A series of controlled scientific field experiments, followed by extended duration production test wells and leading to commercial- scale multi-well demonstrations, are needed to determine the rates and volumes at which methane can be extracted and to assess potential environmental impacts.

Several gas hydrate production strategies are being investigated. Simple depressurization holds the most promise in terms of potential flow rates. However, methane production via carbon dioxide (CO_2) injection is also considered a viable approach that could be adopted for future production systems.

Potential environmental and safety issues associated with different gas hydrate production strategies are also in need of investigation. The geomechanical stability of a hydrate reservoir may change during and after production, so laboratory testing and modeling of different production scenarios prior to a field test are key. In addition, careful borehole and reservoir stability monitoring during a production field test are essential.

Studies of methane in the atmosphere are also needed to develop a more complete understanding of gas hydrate's role in releasing methane into the natural environment. Methane release from hydrates may impact the health of the oceans, and it may contribute to climate change.

Methane gas flare resulting from methane hydrate depressurization test, Daini Atsumi Knoll, eastern Nankai Trough, Japan. Photo credit: JOGMEC.
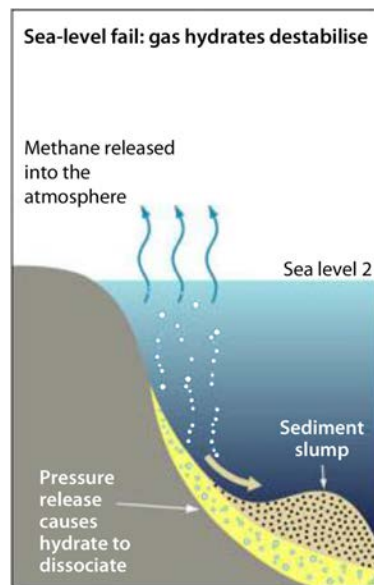
Sea-floor instability.

Pore-filling in coarse grained sand. (Courtesy of Dallmore and Collett, 2005)

Project Portfolio Highlights

The DOE FE Methane Hydrate Program's project portfolio has been formulated to address these knowledge gaps. Most of the R&D projects are field and laboratory efforts being conducted through partnerships with industry and academia and supported by work performed by DOE's National Laboratories and collaborating federal agencies.

Individual methane hydrate projects fall primarily into four categories: 1) production projects; 2) characterization projects; 3) climate change projects; and 4) international efforts. Ongoing and recently completed projects in these categories are summarized as follows.

Production

Investigations of the production potential of onshore gas hydrates associated with permafrost have utilized the natural laboratory of North Slope of Alaska. Projects have been completed in the Milne Point Unit (Mt. Elbert well) and the western Prudhoe Bay region (Ignik Sikumi well).

Mt. Elbert-01 well, in the Milne Point Unit; and PBU L-106 Ignik Sikumi well, Prudhoe Bay Unit. hydrate projects in the Alaska North Slope.
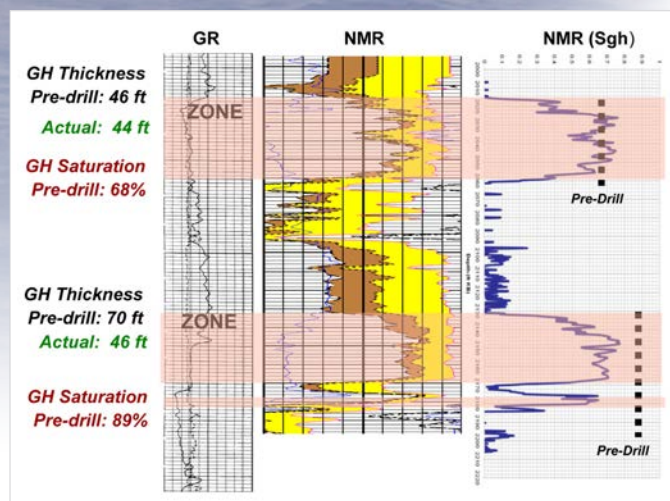
Logs from Mt. Elbert test well in Milne Point field near Prudhoe Bay on the Alaskan North Slope. The gamma ray (GR) and nuclear magnetic resonance (NMR) logs show that pre-drilling estimates of formation thickness and methane hydrate gas saturation (Sgh) based on seismic data were very accurate, supporting the conclusion that seismic exploration tools could be used to prospect for methane hydrate deposits. (Courtesy of Mt. Elbert Science Team).

Gas flare from Ignik Sikumi test well.

The Milne Point project was led by BP Exploration Alaska, with extensive contributions from USGS scientists. In 2006–2008, the USGS analyzed log and seismic data and identified a dozen gas hydrate prospects. The Mt. Elbert well was drilled and tested on one such prospect in 2009, confirming the presence of gas hydrate in reservoir quality sandstone.

Pacific Northwest National Laboratory is completing ongoing modeling efforts focused primarily on the evaluation of CO_2-CH_4 exchange as an effective production strategy.

Lawrence Berkeley National Laboratory is continuing its program of integrated laboratory and numerical modeling to enable the prediction of gas hydrate response to depressurization-induced production. In 2017, LBNL completed initial simulations of a long-term production test at their Indian Hydrates site number nine. LBNL plans to continue with new simulations that focus on reservoir conditions at site number nine.
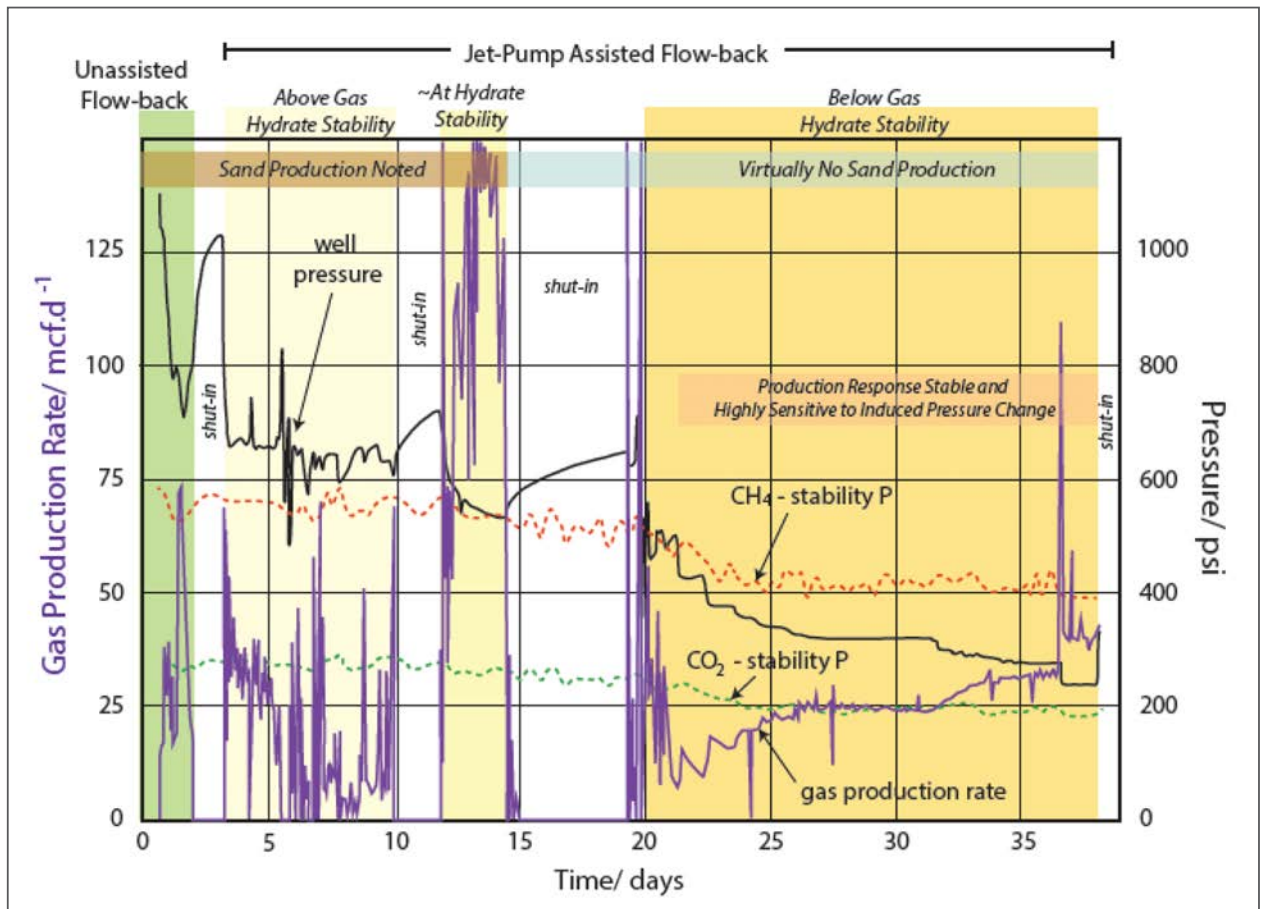
Summary of CO_2-CH_4 exchange production test results, showing well pressure (black line) and gas production rate (purple line) as a function of time. Stages of production are indicated by shading: unassisted flow-back (green shading); jet-pump assisted flowback above gas hydrate stability pressure (tan shading); at hydrate stability pressure (pale yellow shading); and below gas hydrate stability (dark yellow shading). Note that the production was stable after 20 days and clearly responding to induced pressure changes. Sand production, CH_4 stability, and CO_2 stability also shown.

Additionally, NETL is conducting a range of experimental and numerical modeling studies designed to enable improved planning, implementation, and interpretation of DOE-sponsored field programs related to gas hydrate resource potential.

A number of the field efforts described above would not be possible without results derived from the DOE's Fossil Energy Program's fundamental science projects. These projects include laboratory and numerical modeling efforts.

One important project is an international methane hydrate reservoir modeling and numerical simulation consortium. This effort is led by NETL and has resulted in significant advances in all of the leading numerical simulators that are utilized to examine methane hydrate production behavior. Such simulators are essential for accurate planning and predicting methane hydrate production tests.

Characterization

Recent and ongoing marine hydrate characterization investigations have been focused in large part on the northern Gulf of Mexico, with some recent efforts in the Cascadia Margin area of the Pacific Northwest.

A project carried out by a DOE-Chevron Joint Industry Project (JIP) included a comprehensive site selection process for drilling and coring expeditions that took place in 2005 and 2009. In 2005, JIP scientists carried out logging while drilling operations at two sites in the northern Gulf of Mexico in order to develop safe drilling

Used by permission

Map of the geophysical response of the target horizon. Red areas have seismic response consistent with that confirmed to indicate gas hydrate in the WR313-G well.

Derrick of the Q4000 at WR313.

practices in hydrate-bearing areas. In 2009, the JIP conducted a second expedition to drill test wells at three deepwater sites selected using methods that target sand-rich reservoirs. The project resulted in the discovery of several gas hydrate accumulations with 50–80 percent saturation, confirming the effectiveness of pre-drill exploration techniques.

The University of Texas at Austin is currently leading an effort to conduct further gas hydrate sampling and analysis at northern Gulf of Mexico sites discovered by the Chevron JIP in 2009. This new project is currently in the throes of expedition planning and analysis of existing data. Ultimately, the project team will revisit Gulf of Mexico methane hydrate sites for collection of core samples, in-situ measurements, and pressure perturbation testing. Project partners have not ruled out exploring other areas of the U.S. Outer Continental Shelf as well. As of May 2017, the complementary project proposal was approved and the projected start date for a large-scale research expedition is early 2020.

Georgia Tech completed a series of laboratory studies to investigate the behavior of gas hydrates hosted in fine-grained sediments, and the results will be used to evaluate the potential to produce gas from such deposits.

In a related effort, the Colorado School of Mines is conducting laboratory studies to develop a calibration tool that will enable a more accurate estimation of the concentration of gas hydrates from standard seismic data.
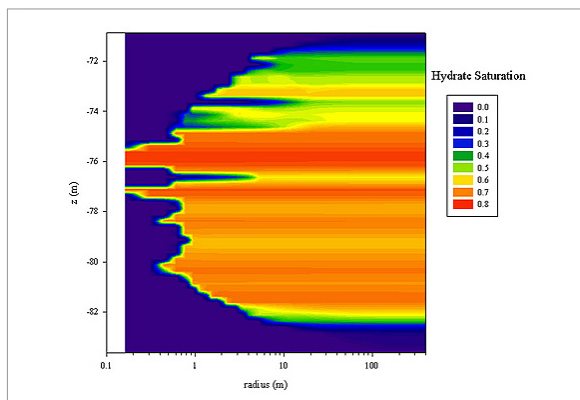
Climate Change

Lawrence Berkeley National Lab and Los Alamos National Lab recently completed an effort to couple leading gas hydrate reservoir simulators and ocean circulation models to enable prediction of the response of marine gas hydrates to changing ocean conditions. The project will also examine the potential impact of marine hydrate destabilization on ocean ecology.

In a project aimed at understanding natural methane fluxes from marine hydrates, Oregon State University has generated computer models to interpret modern day methane fluxes and reconstruct past episodes of methane flux in gas hydrate-bearing regions using shallow geochemical data. The results of this effort help to constrain the biogeochemical processes occurring in the sediments near the sulfate-methane transition zone and are important from a research perspective regarding the role of methane hydrate in global greenhouse gas emissions and climate change.

A 3D tomographic reconstruction of the pore space in a fine grain glass bead pack containing BaCl brine (yellow) where tetrahydrofuran hydrate (violet) has formed. Part of a research effort to relate seismic and acoustic velocities and attenuations to hydrate saturation and texture.
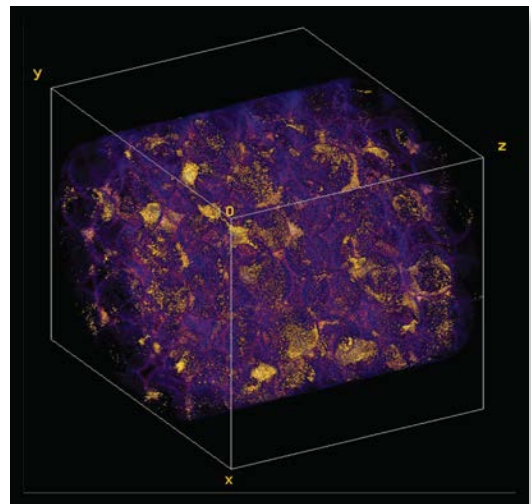

Results of modeling the variation in hydrate saturation in a 10m thick, heterogeneous reservoir (Mt. Elbert C Unit) after 180 days of depressurization at 2.8 MPa.

In an allied effort, the University of New Hampshire has been reconstructing the history of methane flux at three sites on the Cascadia margin, off the coast of Washington State, using data from sedimentary rock layers. This study ultimately identified multiple intervals of diagenetically reduced magnetic susceptibility at three separate sites along the Cascadia margin.
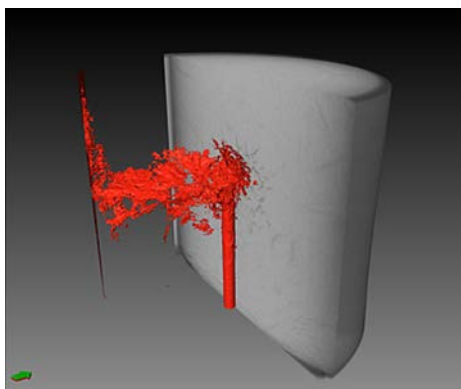
CT scanning image showing gas migration pathways (in red) through a fine grain sediment core (in gray) as part of NETL ORD effort to visualize hydrate within the pore space during the hydrate formation and dissociation processes.

International Efforts

The DOE FE Methane Hydrate Program has collaborated on major international field efforts in recent years, primarily with international hydrate programs in Japan, India, South Korea, and New Zealand.

The Naval Research Laboratory participated in a collaborative field program with New Zealand and Germany to investigate gas hydrates offshore New Zealand. This effort was in support of a research voyage conducted by the New Zealand Gas Hydrates Resources Program to collect acoustic, seismic, and piston cores.

The Japan Oil and Gas Metals Corporation has led several international methane hydrate R&D efforts, with critical contributions from the FE Hydrate Program. Two well-known field programs were carried out successfully in an onshore region of Arctic Canada, known as the Mallik site; and in the deepwater Nankai Trough, off the southeastern coast of Japan. Studies at the Mallik site focused on testing gas hydrate production technologies, while the Nankai Trough work included geophysical surveys, exploratory drilling, as well as short duration production testing. The United States and Japan also collaborated on the Ignik Sikumi Field Trial in Alaska, and the two countries signed an agreement in 2014 to cooperate on additional gas hydrate production testing on state lands on the North Slope of Alaska.

The government of India has also been active in gas hydrate R&D over the past decade, with substantial involvement of the U.S. DOE, USGS, and BOEM. The Indian government led a collaborative drilling and coring program in the Arabian Sea, Bay of Bengal, and Andaman Islands in the past. More recently, Indian scientists have been planning additional drilling locations in deeper water locations for methane hydrate production testing. The USGS has played a pivotal role in planning and executing India's gas hydrate R&D efforts. South Korea has conducted two large-scale drilling programs in their Ulleung Basin region and discovered a wide range of gas hydrate occurrences. Methane hydrate experts from the U.S. DOE and USGS participated in these expeditions and served as scientific advisors to the South Korean Program.

Collectively, these projects provide the fundamental science needed to support the methane hydrate field efforts described above. Laboratory and modeling results, when applied to the various field efforts, contribute to more accurate resource characterization; more reliable resource estimates; more rigorous estimates of a hydrate reservoir's production potential; and more accurate estimates of a hydrate accumulation's influence on and response to its climate and environment.

Tibet (Qilian Mts.)
2009

China (South China Sea)
2007, 2013

Korea (East Sea)
2007, 2010

India (Bay of Bengal,
Andamans)
2006, 2014

Japan (Nankai Trough)
2005, 2012, 2013

Japan–Canada
(Mallik test site),
2007, 2008

USA (Alaska North Slope)
2007, 2012

USA (N. Gulf of Mexico)
2005, 2009

Gas hydrate R&D drilling programs for resource appraised since 2000.

DOE and USGS scientists have participated in a number of recent international scientific expeditions to study methane hydrate in marine settings. This photo was taken during an excursion led by India. (Photo courtesy of Kelly Rose, NETL).
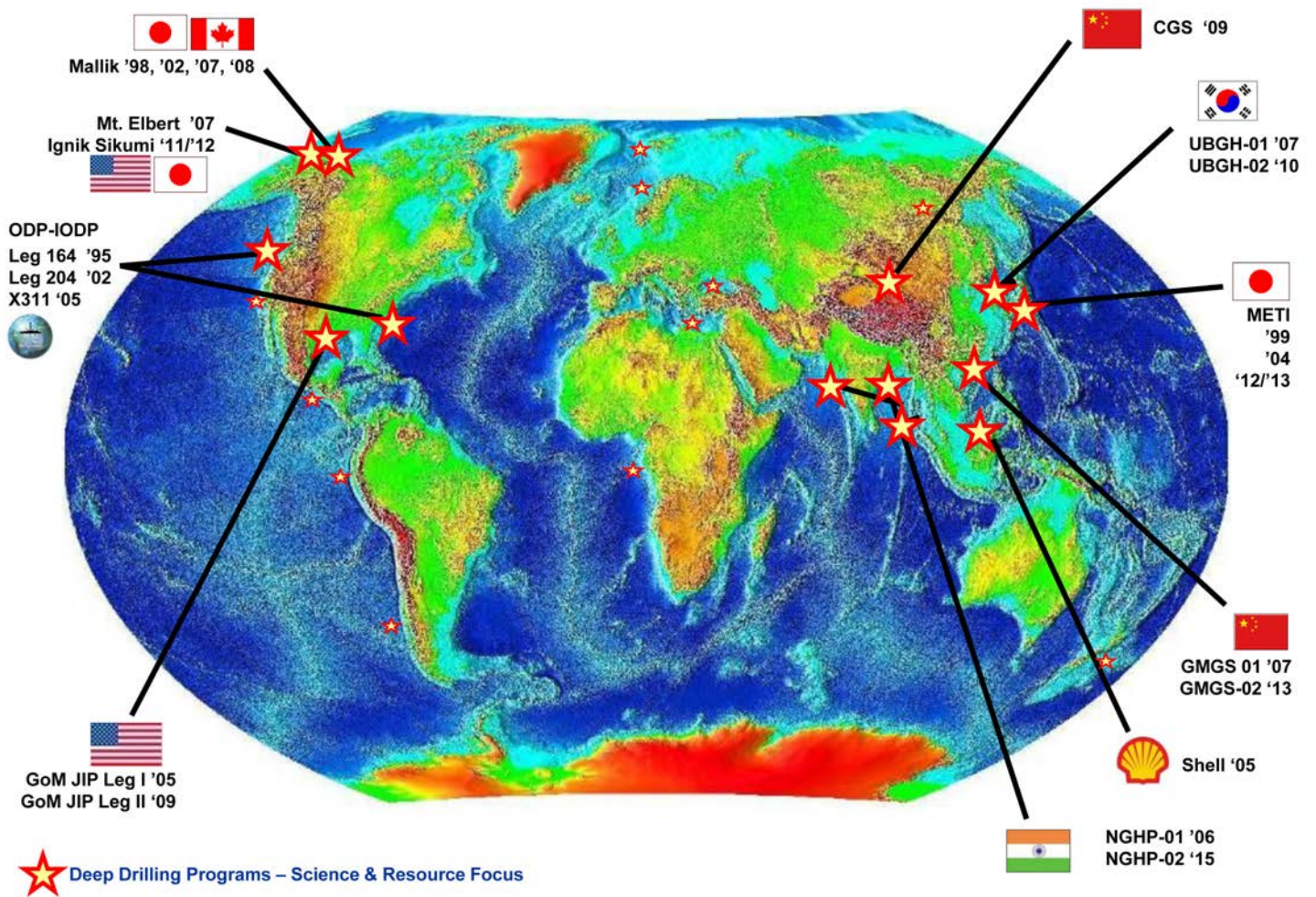
Global gas hydrate R&D "deep" drilling programs during the last 15 years.

Key Accomplishments

> The Gas Hydrates program is working to advance the science and technologies necessary to fully understand the energy resource and environmental implications of naturally-occurring gas hydrate.

Some key accomplishments of the FE Methane Hydrate R&D Program to date include:

• Confirmation of the ability to reliably detect and characterize gas hydrate accumulations prior to drilling, using seismic and well log information;

• Confirmation of the occurrence of resource-quality gas hydrate accumulations in the Gulf of Mexico;

• Acquisition of data in Alaska that has enabled the first quantification of technically-recoverable resource volumes from gas hydrates;

• Development of new tools to enable measurement of the physical properties of gas hydrate-bearing sediment samples acquired in the field;

• Characterization of potential testing sites on the Alaska North Slope, including the drilling and evaluation at the Ignik Sikumi test site in 2011 and a 3-month production trial of CO_2-CH_4 exchange technology during early 2012;

• Development of collaborative agreements with leading global gas hydrate research programs;

• Expansion of numerical modeling capability to enable the first field-scale production, geomechanical stability of hydrate bearing sediment, and gas hydrate-climate change simulations.

Mt. Elbert test site, Alaska North Slope.

METHANE HYDRATE R&D NEEDS GOING FORWARD

In order to move forward and continue to advance our understanding of gas hydrate's role in energy and the global environment, additional targeted scientific research and technology development is needed.

U.S. and international R&D efforts to date have shown that gas hydrates are abundant in nature and exist in a wide variety of forms, with varying relevance to future energy, long-term global carbon cycling, near-term climate change, and natural and operational geohazards. Formal hydrate resource assessments indicate large volumes of domestic hydrate resources in onshore sedimentary strata in Alaska and in offshore sediments in our nation's outer continental shelves.

Drilling programs in Alaska and the Gulf of Mexico have demonstrated the effectiveness of methane hydrate exploration approaches and provided initial confirmation of the technical recoverability of gas from hydrates. In addition, short-duration, scientific production trials have been carried out successfully in Alaska and in the Nankai Trough, off the coast of Japan. Recent and ongoing scientific field programs to evaluate the flux of natural gas in climate-sensitive, gas hydrate-bearing environments promise to provide new insights into the history and causes of methane release from hydrates.

Operational Geohazards
Integrity while drilling or producing through hydrates that lay above conventional hydrocarbons

Global Environment
Linkages to deep sea biological communities, periodic sea-floor instability, global carbon cycling over long time-scales, and potential response to ongoing global climate change.

U. Birmingham – Arctic plumes
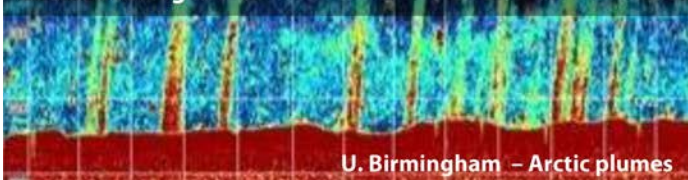
Energy Resource Potential
What types of deposits are the feasible targets and what are the potential resource volumes?

How can they be found?

How can they be produced safely and economically?

JOGMEC, 2013

Importance of gas hydrate R&D as applied to operational geohazards, energy resource potential, and the global environment.

U.S. DOE Hydrate Program Strategy for the Future

In order to move forward and continue to advance our understanding of gas hydrate's role in energy and the global environment, additional targeted scientific research and technology development is needed.

Primary long-term R&D needs are: 1) to provide an accurate assessment of the nature and occurrence of gas hydrates within the U.S.; 2) to identify, refine, and demonstrate technologies that can achieve production of natural gas from gas hydrates in an economically-viable and environmentally-responsible manner; 3) to determine and effectively communicate the role of gas hydrates in natural and operational geohazards; and 4) to elucidate the role gas hydrate plays in the natural sequestration and cycling of carbon over a range of time-scales, including potential short-term responses to ongoing climate change.

The most effective approach to meeting these R&D needs will be to carry out a series of large-scale scientific field programs supported by laboratory and modeling studies. Such field programs will benefit from continued international partnerships, public-private partnerships, and sustained collaboration among federal agencies.

Field programs will be optimized by combining multidisciplinary efforts ranging from geophysical data acquisition, to well drilling and logging, to sampling and analysis, and finally reservoir scientific and production testing.

As a complement to such field programs, it is important to continue targeted laboratory and numerical simulation efforts that improve our understanding of the fundamentals of gas hydrate behavior under the specific conditions found at a particular field site. Methane hydrate field programs also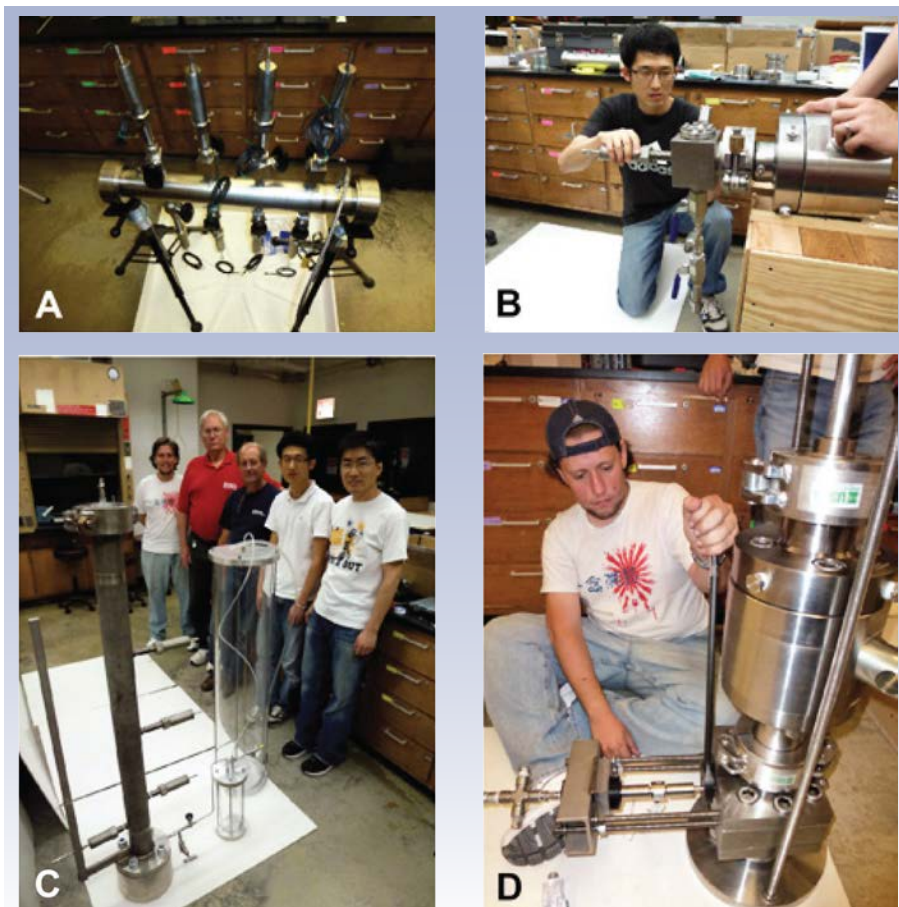 benefit from continued design improvements to hydrate sampling and measurement tools. The devices shown at right are essential for successful recovery, preservation, and analysis of methane hydrate in the field.

Devices essential for successful recovery, preservation, and analysis of methane hydrate in the field: (A) The Instrumented Pressure Testing Chamber (IPTC) showing probe ball valves, drive arms, and the ends of the instrumented probes. The manipulator and IPTC can accommodate core sections up to 1.2 m long. (B) The biological incubation chamber (bottom) can be prepared with a chosen set of nutrients and then receive a core subsection from the bio-sampler (center), which subsamples core material fed through the ball valve (right). A window permits observation of the sample during subsampling. (C) Some members of the Georgia Tech and USGS teams standing with the controlled depressurization chamber. The metal chamber is filled with a hydrate-bearing sediment core that produces water (collected in the small chamber) and methane gas (collected in the large chamber) during controlled dissociation. (D) The direct shear device.

Long-Term Goals (2015-2030)

In keeping with this strategy, the U.S. DOE FE Methane Hydrate Program has identified some long-term goals, to be achieved over the next 15 years.

One goal is to carry out a series of drilling, logging, and coring programs to refine the assessment of viable domestic recoverable gas resource volumes from methane hydrates.

A second goal is to conduct a series of extended duration reservoir response tests that progress from controlled scientific experiments of reservoir depressurization to an integrated technology demonstration in a variety of geologic settings. These tests will enable an improved assessment of the potential for gas hydrate to provide incremental supplies of natural gas to the United States.

An additional long-term goal is to examine and document the role gas hydrate plays in the global environment, including its role in long-term carbon cycling and near-term climate change. Ultimately, these insights will be integrated into forward climate models.

Finally, an important long-term goal is to continue to engage in international collaboration and partnerships, in order to assist in accelerating timelines for R&D achievements and in order to broaden the geographic and geologic base for gas hydrate resource appraisal by key allies.

Near-Term Goals (2015-2020)

While the primary outcomes of a gas hydrate R&D effort are likely to be long-term, there are a number of key steps over the next five years that will help ensure a positive progression toward the long-term goals. Near-term and long-term goals are illustrated on the timeline below.

NATURAL GAS TECHNOLOGIES—SCIENCE AND TECHNOLOGY DEVELOPMENT TIMELINES
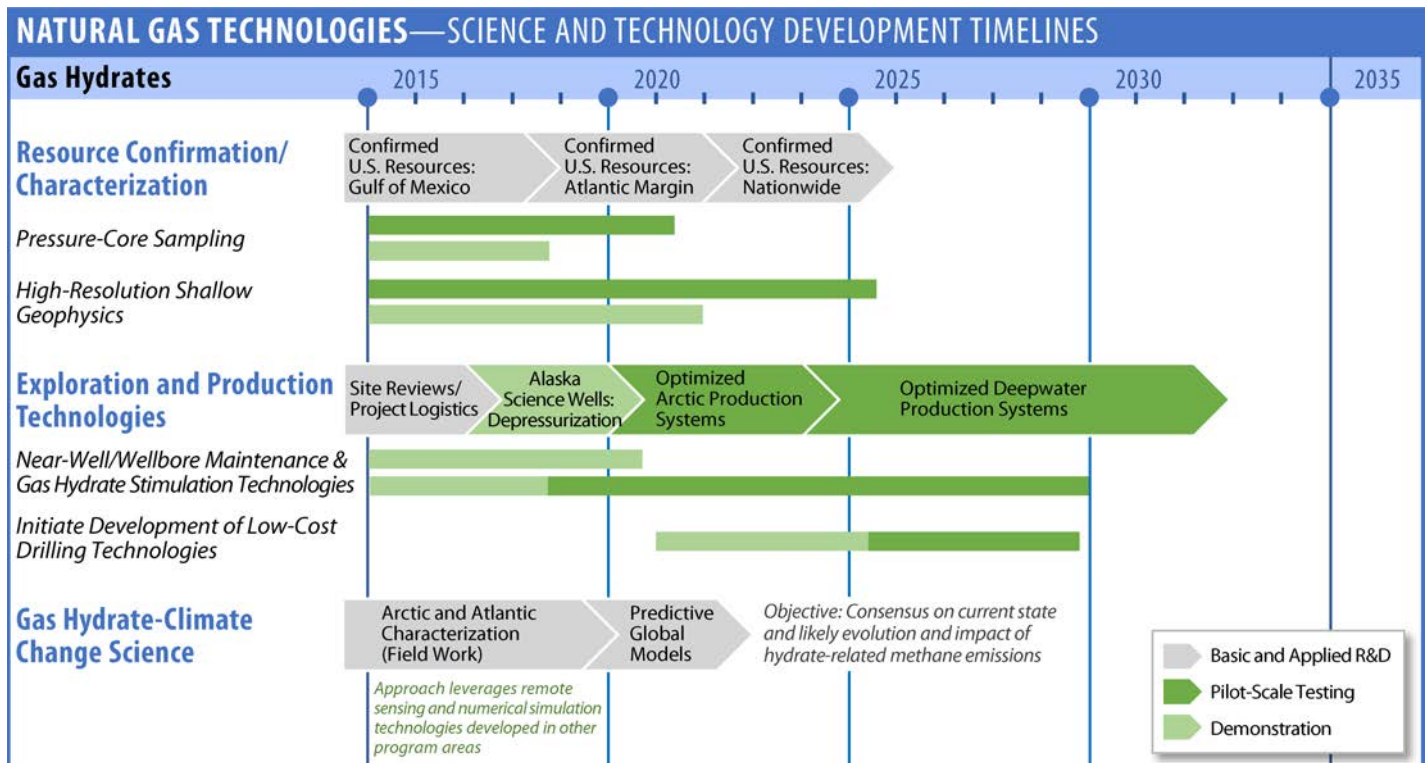
Resource Confirmation

Several near-term goals are related to "Resource Confirmation." The first is to complete field programs in the northern Gulf of Mexico that are aimed at exploring new sites and to collect and characterize pressure cores from existing sites. The second is to initiate field programs to evaluate gas hydrate occurrences on the U.S. Atlantic Margin. The third is to complete testing, development, and deployment of deepwater pressure coring and pressure core analysis systems.

NATURAL GAS TECHNOLOGIES—SCIENCE AND TECHNOLOGY DEVELOPMENT TIMELINES

Gas Hydrates — Resource Confirmation/Characterization: Confirmed U.S. Resources: Gulf of Mexico; Confirmed U.S. Resources: Atlantic Margin; Confirmed U.S. Resources: Nationwide. Pressure-Core Sampling; High-Resolution Shallow Geophysics. Legend: Basic and Applied R&D, Pilot-Scale Testing, Demonstration.

Exploration and Production Technologies

A number of near-term goals fall under the category "Exploration and Production Technologies." One goal is to complete geologic and geophysical studies to confirm reservoir occurrences on State Lands on the North Slope of Alaska. Another goal is to conduct a series of multi-well expeditions at sites in the U.S. outer continental shelf.

NATURAL GAS TECHNOLOGIES—SCIENCE AND TECHNOLOGY DEVELOPMENT TIMELINES

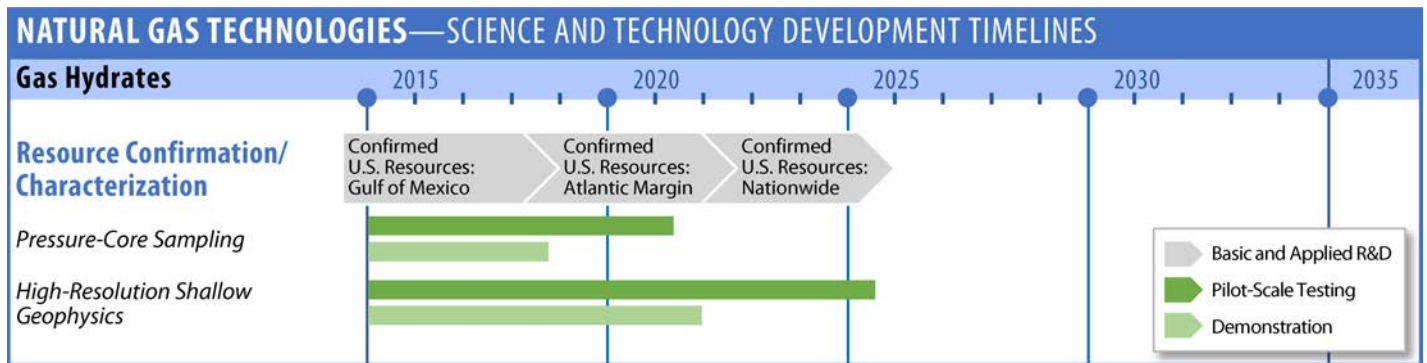Gas Hydrates — Exploration and Production Technologies: Site Reviews/Project Logistics; Alaska Science Wells: Depressurization; Optimized Arctic Production Systems; Optimized Deepwater Production Systems. Near-Well/Wellbore Maintenance & Gas Hydrate Stimulation Technologies; Initiate Development of Low-Cost Drilling Technologies. Legend: Basic and Applied R&D, Pilot-Scale Testing, Demonstration.

These exploration efforts would be designed to select sites and conduct science to address a range of issues, including core acquisition from resource-quality accumulations; development of advanced models of gas hydrate formation and evolution, geohazards, climate interactions; and refinement of resource volume estimates. The primary focus will be on further evaluation of gas hydrate occurrences in areas of high potential as indicated in ongoing BOEM studies, including the northern Gulf of Mexico and the central and northern Atlantic outer continental shelf.

An additional goal is to test exploration concepts in other locations, through collaborative International drilling programs.

A short-term goal for advancing production technologies is to complete an initial scientific production test in Alaska, with focus on determining expected gas and water production profiles to be generated from reservoir depressurization. The test will contain comprehensive environmental monitoring related to gas migration, movement of the dissociation front, geomechanics and land subsidence, water production, air emissions, and water production volumes and chemistry.

Another goal in this category is to analyze the petrophysical and geomechanical characteristics of marine gas hydrates from existing pressure cores and to collect short-duration pressure response data from gas hydrate reservoirs in the Gulf of Mexico.

Global Carbon Cycle

A short-term goal in this area is to complete studies to constrain observed natural gas flux and potential contributions from gas hydrates. This goal also includes development and validation of numerical simulation tools that enable sound planning of field programs and reliable interpretation of field data with respect to gas hydrate energy development, reservoir geomechanics, environmental impacts, gas hydrate role in global carbon cycling (long term) and past climate events, and gas hydrate role in ongoing climate change (present and near term).
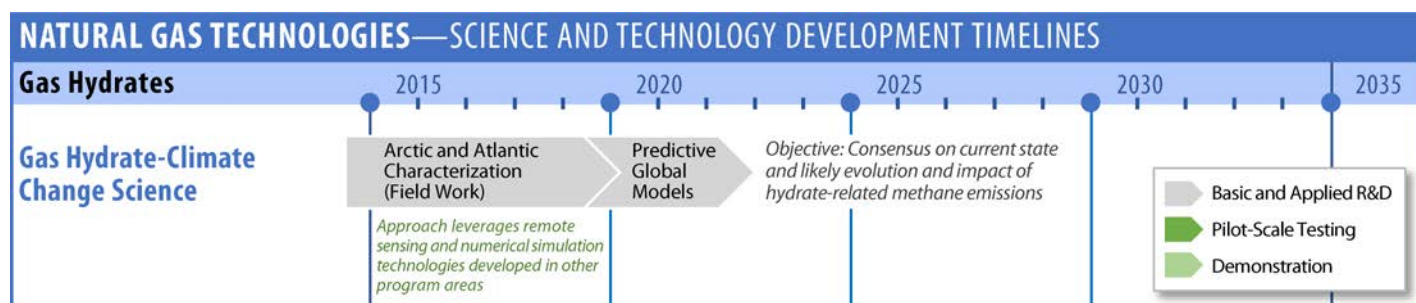
Another goal is to initiate a program of drilling and sampling expeditions in climate-sensitive and geohazard-prone settings to determine typical gas hydrate occurrences and inventories, the rate and nature of changes in the natural environment and the response of gas hydrate-bearing sediment to those changes, the dynamics of natural gas flux, and the impact of natural gas on oceanic and atmospheric chemistry. It is anticipated that such an expedition would target gas hydrate in permafrost-associated settings, in offshore settings, and in areas of natural gas seepage within the zone of gas hydrate stability. Efforts to integrate gas hydrate science and global climate modeling are also a priority.

International Collaboration

A short-term goal under "International Collaboration" is to strengthen collaborative ties with key allies and develop new partnerships as opportunities arise.

Technical Focus Areas for Short-Term Activities (2015–2020)

Six technical focus areas have been identified for R&D work needed to meet short-term program goals over the next five years:

1. Development of tools for reliable marine gas hydrate sampling and analysis;

2. Integrated geologic/geophysical characterization methodologies to enable pre-drill assessments of natural gas hydrate systems;

3. Development of exploration technologies;

4. Development of production technologies;

5. Determination of gas hydrate's implications for long-term global carbon cycling and potential near-term feedbacks to ongoing climate change; and

6. Development and demonstration of effective numerical simulation tools to enable the effective design and interpretation of field data related to both production and environmental implications.

Marine Sampling Tools/Technology Development

Given the difficulties in preservation and transfer of natural samples into laboratory equipment, and the complexities of creating synthetic samples that sufficiently mimic natural conditions, strong emphasis will continue to be placed on development of in situ data collection tools.

A high priority R&D activity is to complete the development of a robust coring system that has the flexibility to successfully acquire and analyze cores from a variety of common drilling platforms and across a range of occurrence types, including gas-hydrate-bearing sands. These systems include both the coring device and a suite of compatible analytical devices that can collect physical and chemical property data from minimally-disturbed samples. Opportunities to further the development of these tools through domestic and international collaboration will be pursued.

Gas Hydrate Systems Characterization

In order to improve our understanding of the controls on the abundance, occurrence, and nature of gas hydrates in sediments, a large survey of methane hydrate occurrences may be necessary. An effort will be made to obtain data from a wide range of environments where gas hydrate is theoretically stable, but its actual occurrence is highly variable.

A primary near-term R&D activity in this focus area will include geologic and geophysical review, of gas hydrate occurrence on state lands in Alaska. A second action will be to pursue opportunities for deepwater drilling and sampling in the U.S. outer continental shelf, most likely in association with known sites in the northern Gulf of Mexico. A third action is continued international engagement in drilling and coring expeditions.

Gas Hydrate Exploration Technologies

A number of highly concentrated methane hydrate deposits have been located successfully using exploration approaches that fully assess the local petroleum system—using a balanced analysis of local gas sources, suitable host reservoirs, and gas migration pathways. This type of exploration approach appears to be sufficient for the recognition of a gas hydrate sweet spot or anomalously rich accumulation. However, it is likely that many more viable hydrate deposits exist in nature and will only be identified through more sophisticated data acquisition and analysis approaches.

In the near-term, additional prospect development (in Alaska and in the Gulf of Mexico) and subsequent exploratory drilling will be essential to more fully develop sound and effective gas hydrate characterization methods. Longer-term, the program will apply these insights to the evaluation of gas hydrate in other high-potential regions of the U.S. outer continental shelf, such as the Atlantic Margin; or to areas where gas hydrate characterization could better constrain potential geohazards, such as offshore northern Alaska.
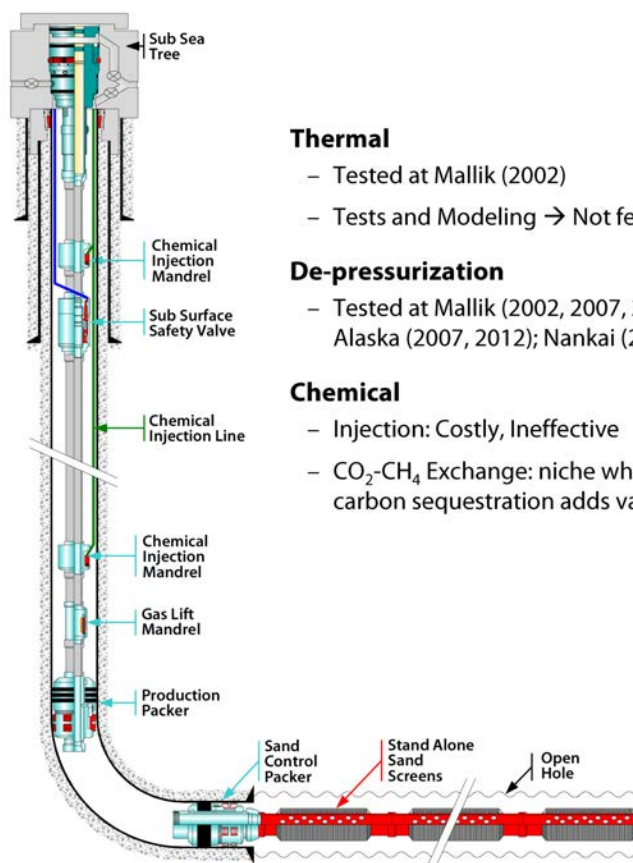
Gas Hydrate Production Technology

Short-duration scientific field tests of gas hydrate productivity have been conducted at locations in Arctic Canada, Alaska North Slope, and in the Nankai Trough, offshore Japan. These tests have revealed that the primary technology for gas hydrate production will be reservoir depressurization; although it is expected that local optimization of production will include use of supplemental stimulation technologies, such as heating and chemical injection as most appropriate for local conditions.

While these tests have demonstrated the technical feasibility of methane hydrate production, achieving economic viability will require overcoming a range of complex technical and operational challenges.

A primary near-term R&D need is to conduct extended-duration scientific field tests that will provide a sound understanding of the physical response of gas hydrate reservoirs to reservoir depressurization. Such testing would ideally include comprehensive monitoring to track the dissociation front, the migration and/or release of any free gas, and the geomechanical response of reservoirs and seals. Over the longer-term, subsequent tests can be designed to assess the potential long-term gas and water production profiles that can be expected from optimized production systems across the range of likely gas hydrate occurrences.

Thermal
- Tested at Mallik (2002)
- Tests and Modeling → Not feasible

De-pressurization
- Tested at Mallik (2002, 2007, 2008); Alaska (2007, 2012); Nankai (2013)

Chemical
- Injection: Costly, Ineffective
- CO_2-CH_4 Exchange: niche where carbon sequestration adds value

Production Technology.

The most favorable location for long-term production testing at this time is the Greater Prudhoe Bay region on the North Slope of Alaska. This area includes the well-characterized reservoirs of the Milne Point, Prudhoe Bay, and Kuparuk River oil fields. The DOE is currently working closely with Industry, the State of Alaska, the USGS, and JOGMEC to overcome logistical barriers to conducting the testing in this region.

Gas Hydrate Geohazards

Gas hydrate has been linked to a range of issues collectively described using the term "geohazards." These hazards generally relate to the consequences of gas hydrate dissociation and the destabilizing effects of relatively sudden introduction of large volumes of gas and water into shallow geologic systems.

Gas hydrate geohazards include events that occur due to natural processes or that are triggered unintentionally by industrial activities.

Although this technical focus area has attracted past private industry investment, no ongoing industry research on this topic is known. The unique setting of gas hydrate on shallow Arctic shelves, and the high environmental sensitivity of those regions, suggests that further research on this topic is a priority. Primary near-term actions will focus on designing various field programs to assess natural geohazard issues that may arise in both deepwater and arctic environments.
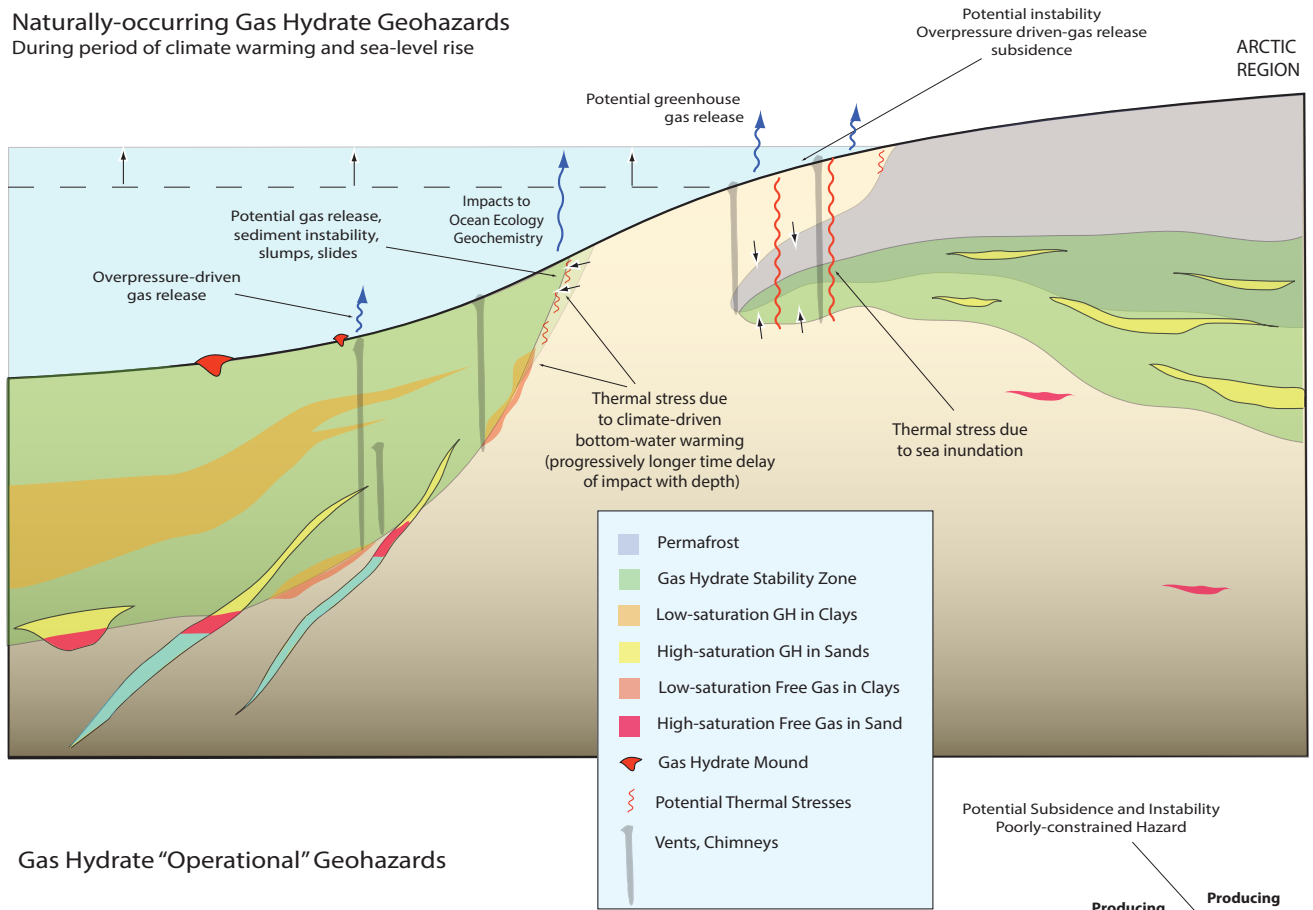
Gas Hydrate Linkages to Global Carbon Cycling and Climate Change: In recent years, there has been growing concern that methane venting from the sea-floor may be a common global occurrence. This phenomenon, particularly as it may relate to events in the Arctic, has fueled concerns that gas hydrate destabilization and natural gas release pose a substantial risk as a deleterious feedback to ongoing climate change.

Current information and models are not sufficient to assess the climate risks of gas hydrate – to do so, they will need to be based on accurate depictions of gas hydrate occurrence and distribution in climate sensitive settings; proper accounting for the timescales needed to destabilize gas hydrates given specific climatic changes; and full integration of the potential sinks that may mediate the delivery of any released natural gas to either the ocean or the atmosphere.

To address these questions, our FE Hydrate Program will initiate a systematic program of field study to delineate those areas most prone to climate-induced destabilization and to better constrain the assessment of the distribution of gas hydrate within those regions. These field-based efforts should ultimately investigate a variety of gas hydrate-bearing areas and the resulting data should be fully integrated in various process models and ultimately into forward climate models as appropriate.

The overall goal is to contribute to the development of a general scientific consensus regarding the potential response of gas hydrate to different future climate scenarios and the resulting environmental implications. This work should include shallow arctic shelves as well as the landward limit of hydrate stability throughout the U.S. outer continental shelf, and it is likely to be elucidated by studies of past gas hydrate-climate linkages.

Naturally-occurring Gas Hydrate Geohazards
During period of climate warming and sea-level rise

ARCTIC REGION

Potential instability
Overpressure driven-gas release
subsidence

Potential greenhouse gas release

Potential gas release, sediment instability, slumps, slides

Impacts to Ocean Ecology Geochemistry

Overpressure-driven gas release

Thermal stress due to climate-driven bottom-water warming (progressively longer time delay of impact with depth)

Thermal stress due to sea inundation

Legend:
- Permafrost
- Gas Hydrate Stability Zone
- Low-saturation GH in Clays
- High-saturation GH in Sands
- Low-saturation Free Gas in Clays
- High-saturation Free Gas in Sand
- Gas Hydrate Mound
- Potential Thermal Stresses
- Vents, Chimneys

Gas Hydrate "Operational" Geohazards

Potential Subsidence and Instability
Poorly-constrained Hazard

Drilling Through GH

Producing Through GH

Producing From GH

Drilling Through GH

Drilling Through GH

Producing Through GH

Producing From GH

Likely subsidence and instability Poorly-constrained Hazard

Mitigate via proven avoidance methods

Mitigate via known completion approaches Poorly-constrained hazard

Mitigated via known drilling protocols

Mitigate via known drilling protocols

Mitigate via proven avoidance methods

Sediment mobilization Poorly-constrained hazards

Sediment mobilization? Poorly-constrained hazard

Mitigate via proven avoidance methods

Free-gas fully masked by hydrate Poorly-constrained hazard

Warm Fluids

Warm Fluids

Technology Transfer and Outreach

The FE Hydrate R&D Program is committed to ensuring ongoing and effective communication of all significant program findings to the public. Significant R&D findings in the realm of resource confirmation, exploration and production technologies, atmospheric carbon cycling, and global climate change will all be reported in an open and balanced way.

Methane hydrate is known to have played an important role in the global carbon cycle throughout geologic history, as both a source and a sink for atmospheric carbon. Moreover, given strong links between fossil fuels and anthropogenic climate change, it is essential to examine and discuss insights about the role methane hydrates as an energy fuel may play in future climate perturbations.

Through its National Energy Technology Laboratory, the DOE maintains a comprehensive website that is continually updated and provides detailed overviews of completed and ongoing projects. The website also includes links to project reports, project presentations, DOE/NETL program documents, including the recent gas hydrate science review by the United Nations Environmental Programme. In addition, the website includes current and back issues of NETL's methane hydrate newsletter, *Fire in the Ice,* which continues to be a leading source of information for the international gas hydrate R&D community.

SUMMARY

The fundamental needs in gas hydrate R&D are the development of science and technology that enables an accurate assessment of the nature and occurrence of gas hydrate within the U.S.; refinement and demonstration of technologies that can achieve production in an economically-viable and environmentally-responsible manner; and a more complete understanding of the role of gas hydrate deposits in geohazards and in the natural sequestration and cycling of carbon.

Recent assessments published by the USGS and the BOEM have identified extensive gas hydrate resources in sedimentary strata beneath the North Slope of Alaska, the Gulf of Mexico, and the Atlantic and Pacific continental shelves of the United States. These assessments have been aided and validated by successful field programs led by the U.S. DOE's FE Methane Hydrate R&D Program. In addition to developing and demonstrating effective methane hydrate exploration and characterization techniques, the FE Hydrate Program has provided ground-truth through drilling, logging, and sampling that has been used to calibrate and refine resource estimates.

Successful field programs in the United States and in offshore regions of Japan, India, and Korea have served to confirm the presence of the hydrate resource and, in some instances, to demonstrate the technical feasibility of producing methane from hydrate deposits. Nonetheless, additional field validation and calibration is needed before the U.S. gas hydrate resource potential can be understood with confidence.

Gas hydrate also represents a potential risk to global climate that must be properly assessed and evaluated. Methane hydrate R&D going forward will need to continue

to augment private-public partnerships through sustained collaboration across agencies and with international partners. DOE, in its role as primary sponsor of extramural R&D, will ensure program quality, transparency, and relevance through external peer review and will manage the work to ensure that the nation's best talent from industry, academia, and government, are brought to bear on the most critical issues in the field of naturally-occurring gas hydrate.

The fundamental needs in gas hydrate R&D are the development of science and technology that enables an accurate assessment of the nature and occurrence of gas hydrate within the U.S.; refinement and demonstration of technologies that can achieve production in an economically-viable and environmentally-responsible manner; and a more complete understanding of the role of gas hydrate deposits in geohazards and in the natural sequestration and cycling of carbon in response to both long-term (global carbon cycle) and short term (potential feedbacks to ongoing climate change) time-scales.

Successful R&D in these areas will result in a rigorous scientific evaluation of the potential for gas hydrate to provide an additional option to meet future energy needs both for the United States and for key international allies. Results will include demonstration of safe and efficient exploration and production technologies, as well as an understanding of potential environmental impacts and mitigation strategies.

An additional outcome will be an improved understanding of our natural environment, providing more informed decision-making on a wide variety of issues ranging from ocean policy to global climate change. Other benefits are also expected, including successful collaboration with key international partners, a more complete understanding of gas hydrate-related geohazards, and contributions to the education and training of the next generation of scientists.

How to Learn More

Information about methane hydrate research being conducted by the DOE and its domestic and international partners can be found on the DOE's Methane Hydrates website.

The DOE's Fire in the Ice newsletter is published several times per year and contains articles and news items highlighting methane hydrate R&D activities taking place in the United States and around the world.

A wealth of information on methane hydrates can be found in the two-volume report published in March 2015 by the United Nations Environment Program, "Frozen Heat: A Global Outlook on Methane Gas Hydrates."

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